A hand heating enclosure for clinical applications

Introduction

The usual method of obtaining serial arterial blood samples during clinical imaging is via catheter placement into an artery. In general, placement of an arterial line in the radial or femoral artery is awkward, painful and provides an unnecessary risk and discomfort to the patient. The purpose of obtaining arterial blood is to obtain either blood coming directly from the heart and lungs to measure the concentration of a contrast agent or to obtain concentration measures in the whole body. The former technique is still best done via direct arterial sampling, but the latter may be performed in other ways.

Although humans sweat to reduce body temperature through evaporative heat loss, heat can also be lost directly through conduction and radiation by opening up capillaries to increase blood flow through the skin. This second mechanism is more important when cooling of the hand is required, and is activated through opening up of capillary beds. This cools the hand by providing cooler blood when the hand temperature rises above 37°C: Although the venous effluent from a heated hand is not true arterial blood, it is nevertheless a good representation of it. Professor D. Matthews (http://www.uvm.edu/~dmatthew/dem_res/?Page=heated_hand.html) has used this method for a number of years, and several of his publications have provided inspiration to develop the device presented in this note.

The key requirement to obtaining 'arterialized' blood from the vein of the hand is thus to increase the hand skin temperature to the range 37°C – 42°C. Any temperatures higher than 42.5°C are considered to be unsafe. The simplest and cleanest way of warming the hand is by placing it in a gentle stream of hot (heated) air. The arrangement described here is shown in Figure 1. The hand heater consists of a Perspex case 418 mm long x 310 mm wide x 230 mm high. On the back end of the Perspex case a cast aluminium box is mounted. This contains all the electronics and is 110 mm long x 280 mm wide x 230 mm high. Total weight is just below 11 kg.

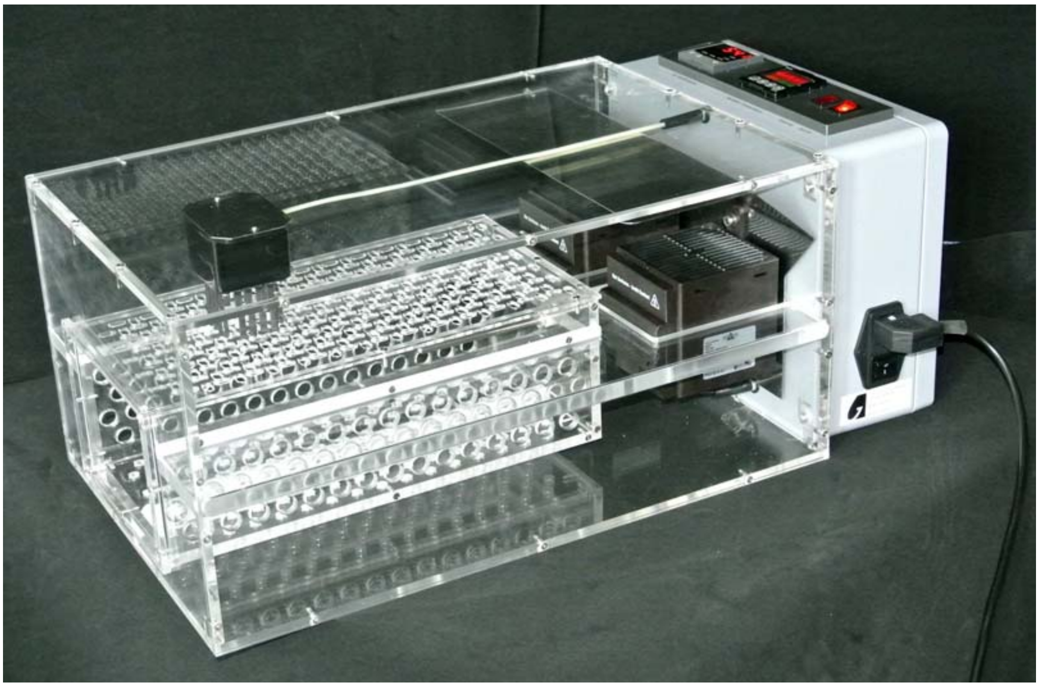

Figure 1. The hand heater unit, consisting of a control and temperature monitoring unit (right), two fan heaters (middle) and a retractable, air-flow-transparent enclosure (left) into which the hand is placed.

Construction details

The hand heater consists of three interconnected unit: a transparent Perspex enclosure, an internal hand 'drawer' enclosure, also made out of Perspex, but with a large number of holes to make it also transparent to air flow and an aluminium electronic control enclosure. These items, as well as other internal components are shown in Figure 2. Within the main enclosure, two integrated heater and fan assemblies are placed below a stainless steel cowling. These are used to heat and re-circulate the air within the enclosure. The use of two fans ensures that good air flow is ensured, without high velocities and consequent potential noise and without significant air trapping. A total of 800 W maximum heating power is provided, more then enough to make up for enclosure (and hand) heat losses. However, by using a high heating power, rapid heating of the enclosure is achieved.

Of course, the heater power is regulated and monitored to prevent overheating. The fan-heater assemblies are inherently protected as the heater elements use a semiconductor positive temperature coefficient resistive material, where the total power deposited decreases with increasing temperature. Two temperature sensors are provided. Both are resistance temperature detectors (RTDs) and use platinum in the form of Pt100 sensors (calibrated resistance of 100 Ω at 25 degC and a linear temperature response (http://en.wikipedia.org/wiki/Resistance_thermometer). One of the sensors (a rod type 'hand air temperature sensor' in Figure 2) measures the temperature within the hand enclosure; this value is used to regulate the heater power, exploiting the fast response of this type of sensor. A second device ('enclosure air temperature sensor' in Figure 2) responds much more slowly and is used to indicate the average temperature of the air above the hand, in a region close to the hand box opening. This sensor temperature is used principally for display purposes. However, it is also used as an over-temperature monitor, cutting off all power to the heater once a preset temperature 'alarm' level is exceeded.

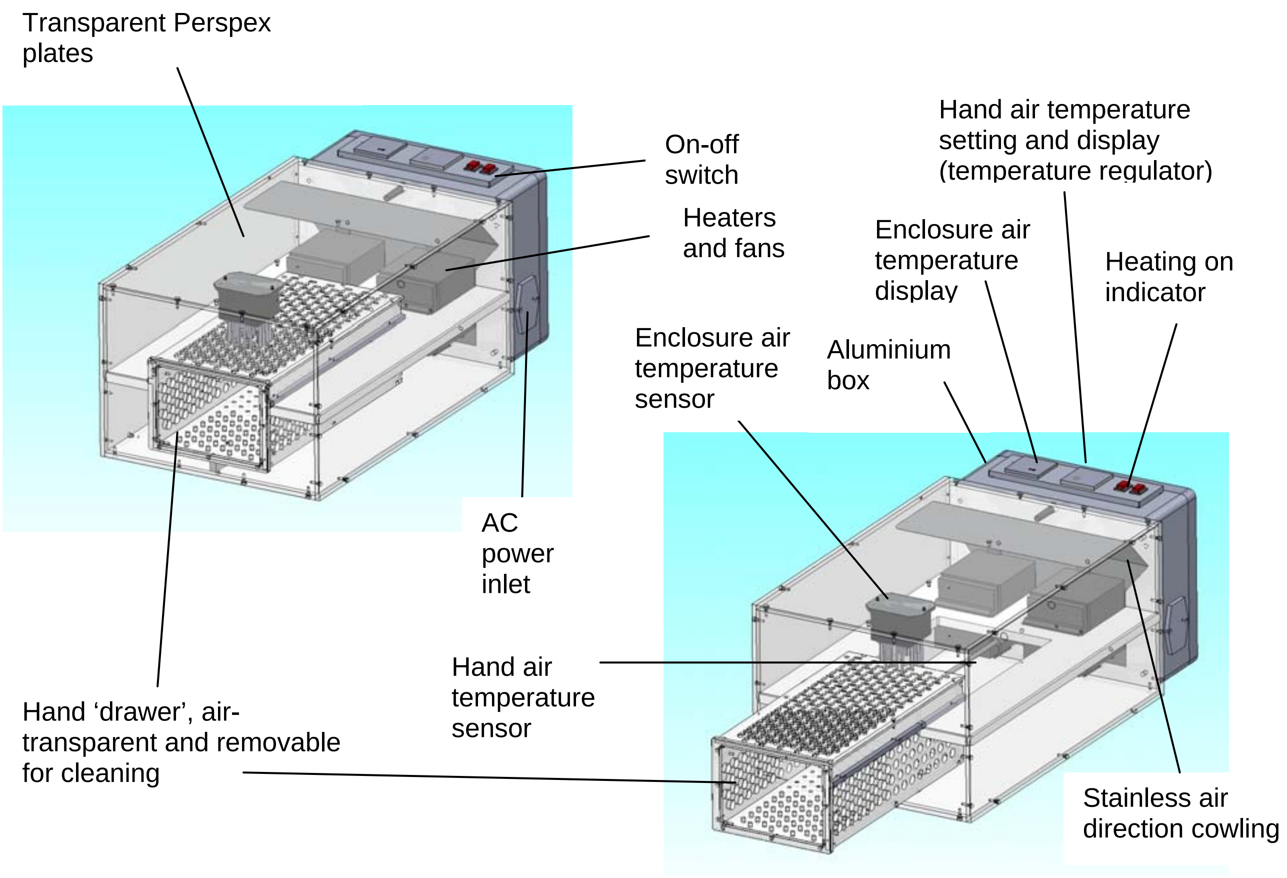

Figure 2. The hand heating system shown with the hand drawer inserted in the heated box (top left) and the hand drawer pulled out (bottom right).

A transparent ‘shelf’ separates the upper and lower parts of the Perspex enclosure and fits around the fan heaters; it ensures that the airflow within the enclosure passes through the multiple holes in the hand-warming drawer.

The circuit diagram of the controller is shown in Figure 3. Mains power (240 V ac) is used to provide power to the unit through a medical rated radio-frequency filter unit in a standard IEC power connector.

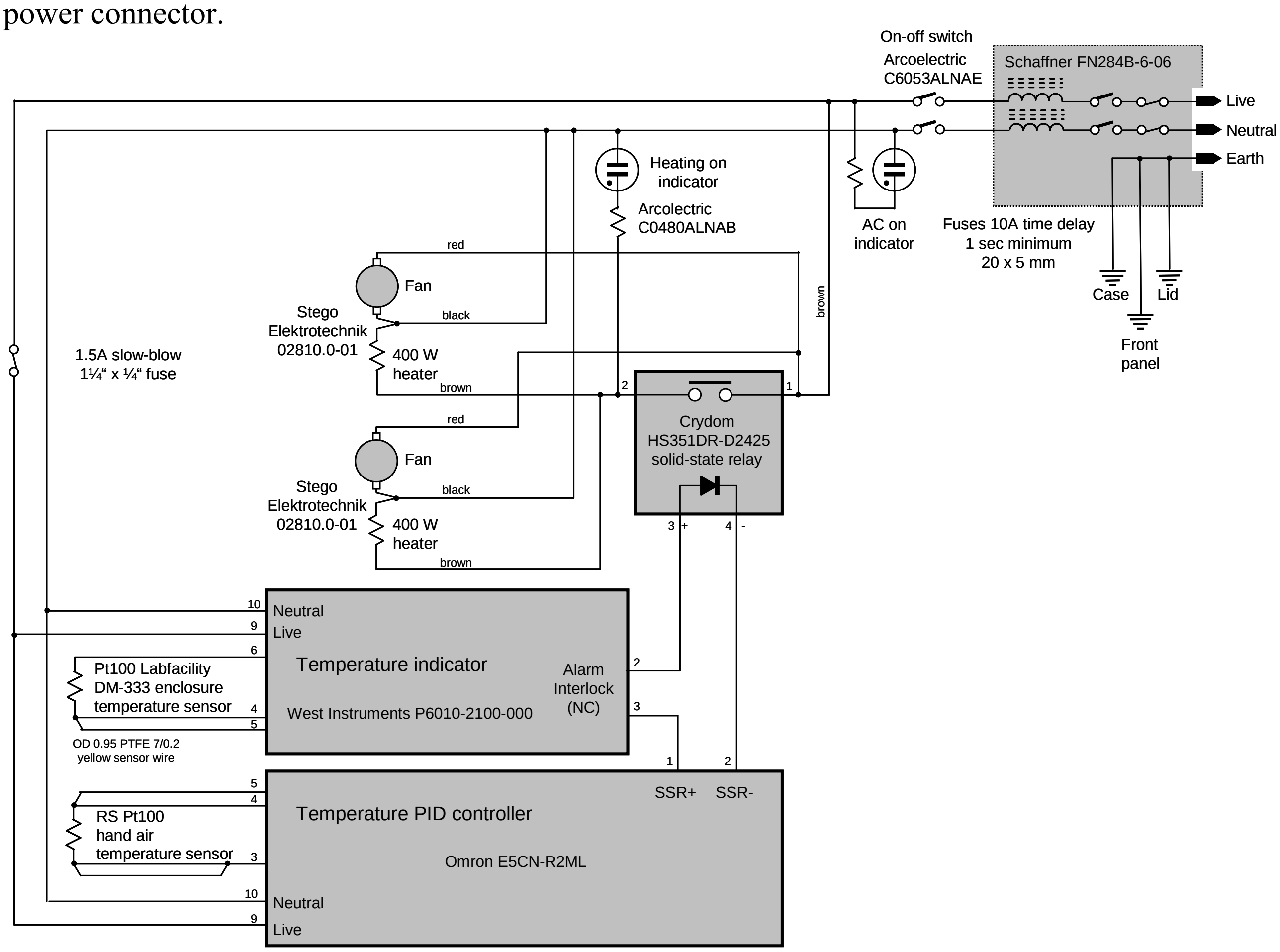

Figure 3. Electrical circuit diagram of the heater, temperature monitor and controller. Please see text for explanation.

A top panel illuminated isolation switch acts as the on-off switch. The fans are powered all the time that the unit remains switched on while heater power is routed through an optically isolated solid-state switch. A proportional-integral-derivative (PID) controller provides the switch drive signal, but this control signal is routed through relay contacts in the enclosure temperature display unit. The hand air temperature sensor is connected to the temperature PID controller. An internal lower current fuse independently fuses both the controller and the average air temperature display/alarm unit.

The unit is only suitable for operation at 240 V ac. Although the controllers can operate at 117 V ac, at least the fan-heaters and the solid-state relay need to be replaced and rated for lower voltage/higher current operation. It is also advised to replace the IEC socket with one suitable for higher current operation.

The completed device is shown in Figure 4, along with a close-up of the user controls.

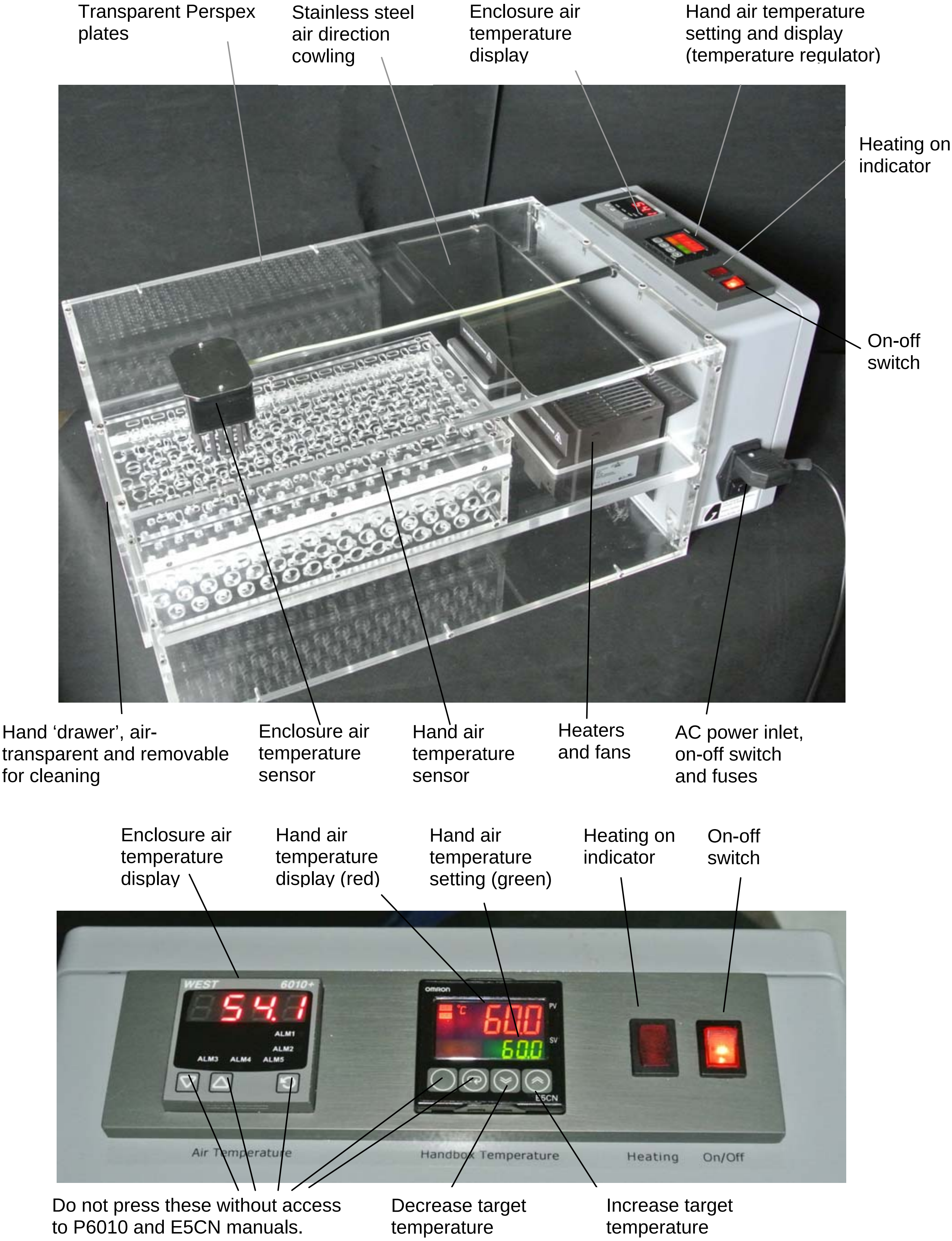

Figure 4. The hand heater (top) and its control panel (bottom).

Tuning and performance

The unit takes no more than 3-4 minutes to reach the target temperature with a few degrees of overshoot (typically less than 5 degC) when the target temperature is set to 60 deg C, starting from normal ambient room temperature. Within 10 minutes, the controlled temperature (e.g. 60 deg C) settles and is maintained to within ±0.5 degC. Similar stabilities are achieved at lower and higher set-point temperatures. However, when the target temperature is required to be close to ambient temperature (e.g. <30 degC), regulation is inevitably impaired, but it is still well within ±1 degC.

It is of course essential to tune the proportional-integral-derivative control loop to attain this level of performance. Please refer to the E5CN manual (front page is shown in Figure 5) on the correct procedure to tune the PID loop. This PID gain factors can be set manually, although it is probably simpler for the system to perform an automatic tuning procedure. This takes several tens of minutes to complete and should be activated at temperatures somewhat higher than ambient (say with the air temperature within the unit at ~40 degC). Anybody not familiar with PID loops should read one of the numerous excellent documents available on the web describing control loops. Amongst the more readable ones are:

http://en.wikipedia.org/wiki/PID_controller; http://www.csimn.com/CSI_pages/PIDforDummies.html and http://electronicdesign.com/analog/whats-all-p-i-d-stuff-anyhow

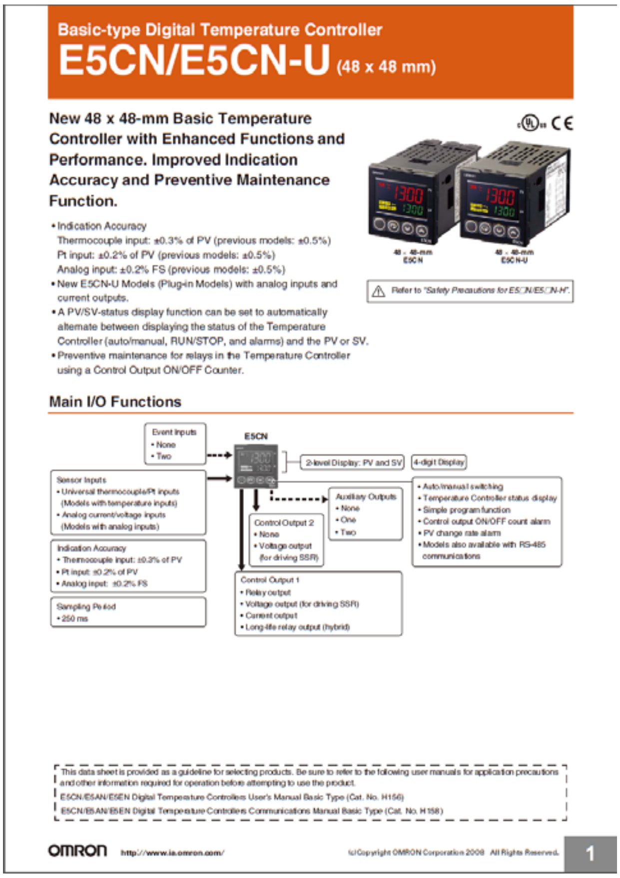

Figure 5: The hand air temperature controller manual front page.

Figure 6: The P6010 enclosure air temperature monitor and alarm unit manual

The default values, after autotuning to a target temperature of 60 degC were: Proprtional gain: 10.6; Integral gain: 76; Derivative gain 13. However well the controller performs, there is always a risk that an over-temperature state can exist. Two measures are provided to counteract this possibility: (1) the range over which the set-point (target) temperature operate are restricted to some value (typically 70-75 degC) and (2) the enclosure air temperature is monitored and the indicator unit is arranged to cut off the power to the heaters above a user set value. The enclosure air temperature, as monitored by the long time constant sensor, is typically a few degrees lower than the hand air temperature. This is because the airflow around that sensor is poorer than that around the hand air temperature, since it is near the top front corner of the enclosure. The alarm value should thus be appropriately set. Please refer to the manual for the P6010 temperature indicator, its front page is shown in Figure 6. Changing the alarm trip point is intentionally made awkward to prevent accidental mis-setting. The procedure is briefly outlined below.

Hold down the ↺ button and press △ button to enter the 'select' mode.
Press the △ or ▽ buttons to get to CONFIG then press ↺ button.
UNLOCK will be displayed, indicating an unlocking code number needs to be entered,
The code number 20 needs to be entered by using the △ or ▽ buttons.
Press ↺ after correct number has been set.
You should now be in CONFIG mode,
Scroll through the parameters until you arrive at PhA1 (high alarm).
Set the required temperature using the △ or ▽ buttons.
Do not exceed 70 degC
Press ↺, YES will then be displayed. Press △ to accept change otherwise the alarm temperature will revert to previous value.
Hold down ↺ and press △ to return to normal control
Then wait for two minutes without pressing any key.

The Omron E5CN controller can then be operated by using the ↑ ↓ buttons to change the set value for the target temperature.

It is noted that a solid-state relay is used as the main switching element between the controller and the heaters. This is significantly over-rated and is thus considered very reliable. It is also noted that, should this ever be required in the future, the P6010 temperature indicator can be fitted with additional outputs to any remote alarm or monitoring stations through a digital link. This facility has not been fitted at time of construction but can be retrofitted using appropriate internal modules.

There are no user-serviceable parts inside the controller assembly and the aluminium enclosure lid should only be removed by electrically trained personnel. Lethal voltages are present on various components inside. All other connections inside the Perspex enclosure are double insulated.

Power consumption and fuses

The device uses two heaters each rated at a maximum of 400W, so the total power consumption, shortly after switch on and at low enclosure temperature is only slightly higher than 800 W. This corresponds to no more than 3.4 A on 240 V mains as used in the UK. However, the peak current, at switch on, is significantly higher and could reach several tens of amps. For this reason, the mains input fuses are rated at 10 A and feature a time-delay characteristic. In the unlikely event that the fuses require replacement, they should only be replaced with the same type of fuse as indicated in the components list, or a device with equivalent time delay characteristics. Once the device has reached operating temperature, the average power consumption is significantly lower, and is typically in the range of 50-100 W, depending on target temperature.

Normal operation

It is advised to switch on the unit at least 15 minutes before hand insertion and set the required target temperature. The hand skin temperature should be monitored independently with a medically compliant sensor (e.g. http://www.meas-spec.com/product/t_product.aspx?id=4290, Measurement Specialities 409A sensor connected to a independent display. Skin temperature should not be allowed to exceed 42.5 degC.

Hand heating enclosure components

Electronics

Item	Note	Manufacturer / model	Supplier Part no.	Qty	Price (£)
Enclosure	IP66 Al enclosure,280 x 230 x 110 mm	Rose 01232811	RS Stock 222-733	1 off	108.86
Plastic box for temperature sensor	Box, ABS, black, 18x40x28 mm	Camden-Boss BIM2008/IP-BLK	RS Stock 528-589	1 off	3.02
Secondary Temperature sensor	Pt 100 type 2 x 10 mm	Labfacility DM-333	One Call 859-8533	1 off	4.40
Heatsink	Transmits air temperature to sensor	Aavid Thermalloy 500400B00000G	RS Stock 103-910	1 off	2.29
Cable sleeving	ID 2.84 mm 5 m length PTFE sleeve	Pro Power SFTE10-5MNAT	One Call 119-1049	1 off	5.69
Sensor wire	OD 0.95 PTFE 7/0.2 yellow sensor wire	Global Measurement and Control 91-9642-27	One Call CB11-555	1 off	9.57
PID temperature controller	Thermocouple/Pt 100 input	Omron E5CN-R2ML	RS Stock 535-367	1 off	156.00
Temperature indicator	1/16DIN process contr red 90-264a	West Instruments P6010-2100-000	RS Stock 623-3751	1 off	144.38
Main temperature probe	PT100 Industrial sensor probe class B	RS – not specified	RS Stock 236-4261	1 off	31.42
Heater + fan assembly	400 W with fan	Stego Elektrotechnik 02810.0-01	RS Stock 697-4418	1 off	75.72
Heater + fan assembly	400 W with fan	Stego Elektrotechnik 02810.0-01	RS Stock 697-4418	1 off	75.72
IEC filtered, switched AC power inlet	6 A current carrying capacity	Schaffner FN284B-6-06	RS Stock 455-8929	1 off	24.48
Mains fuse	Ceramic, Antisurge 10A	Multicomp MCF03C-10A	One Call 112-3128	2 off	1.01
Solid State Relay	DIN rail / screw mount 280Vac 20A	Crydom HS351DR-D2425	RS Stock 703-4586	1 off	37.10
Mains on-off switch	15 A peak current 19.3 x 13 mm	Arcoelectric H8553VBNAA	RS Stock 318-042	1 off	1.76
Heater on neon indicator	Red neon indicator 19.3 x 13 mm	Arcoelectric H8630FBNAL	RS Stock 577-550	1 off	1.55
Cable grommets	Takes heater pwr, sensors into enclosure	Pro Power 60218	One Call 432-6283	6 off	0.72
Fuse, internal	1.1/4"X1/4"	Litlefuse 031301.5MXP	One Call 159-6742	1 off	0.35
Fuse holder, in line	For 1.1/4"X1/4" fuse	Bulgin FX0185	One Call 272-188	1 off	2.37
Mains Lead	4 metre length	Pro Power - 3183Y-0.75MMBLK50M	Onecall 133-3093	1 off	2.20
Mains Plug	White 13A mains toughplug	MK Electric 65503 WHI	RS Stock 459-727	1 off	3.29
Mains RA IEC connector	Right angle IEC 10A 240V	Bulgin Components PX0587/SE	RS Stock 048-8905	1 off	1.92
					693.82

Mechanical components

Item	Note	Manufacturer / model	Material	Qty	Price (£)
Left and right side plates	480 x 230 x 6	Plastics Shop	Cast perspex	2 off	18.46
Top and bottom plates	480 x 300 x 6	Plastics Shop	Cast perspex	2 off	24.10
Front plate	300 x 218 x 8	Plastics Shop	Cast perspex	2 off	16.00
Middle core plate	472 x 308 x 12	Plastics Shop	Cast perspex	1 off	26.75
Bottom of internal hand box	326 x 148 x 6	Plastics Shop	Cast perspex	1 off	8.00
Sides of internal hand box	332 x 112 x 6	Plastics Shop	Cast perspex	2 off	16.00
Top of internal hand box	332 x 168 x 3	Plastics Shop	Cast perspex	1 off	8.00
Back of internal hand box	148 x 112 x 6	Plastics Shop	Cast perspex	1 off	8.00
Front flange of hand box	170 x 122 x 6	Plastics Shop	Cast perspex	1 off	8.00
Hand box guide	324 x 20 x 8	Plastics Shop	Cast perspex	1 off	8.00
Hand box runners	6.5 x 6.5 x 332	RS / in-house stock	Delrin	2 off	8.00
Temperature probe support 1	126 x12 mm diameter	RS / in-house stock	Delrin	1 off	6.00
Temperature probe support 2	21 x 12 mm diameter	RS / in-house stock	Delrin	1 off	6.00
Stainless steel air duct	310 x 280 x 0.9	In-house stock	Stainless steel	1 off	15.10
Stainless steel trim	78 x 58 x 0.9	In house stock	Stainless steel	1 off	0.84
Anodising				1 off	20.00
					197.25

The total component cost is well below £1000 and all electronic components can be obtained from RS (http://uk.rs-online.com) and One Call (http://onecall.farnell.com/). Although specialised machining is required for constructing the enclosure, Perspex plates can be obtained cut to size from The Plastics Shop (www.theplasticshop.co.uk/). SolidWorks (www.solidworks.co.uk/) models and drawings can be supplied on request.

This note was prepared during April and May 2013 by B. Vojnovic, with assistance from IDC Tullis, RG Newman and J Prentice. The project was initiated by Geoff Higgins as part of an imaging study. IDC Tullis designed the mechanics, B. Vojnovic thought through the electronics and control system. J Prentice and G. Shortland machined all the components and RG Newman performed electrical construction. We thank D McGowan for help with safety testing and assistance with approvals for clinical use.

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